

How Cosmic Clocks Tick

Pulsars are the most compact material objects in the universe. Their diameter is approximately equal to that of the city of Munich, but they contain the mass of the Sun. These extreme conditions make them ideal test objects for the theory of general relativity, as the work of **Michael Kramer** and his colleagues from the Bonn-based **Max Planck Institute for Radio Astronomy** shows.

TEXT **THOMAS BÜHRKE**

The story begins in late August 1967, when 24-year-old astronomy student Jocelyn Bell, using a new radio telescope, received signals that repeated exactly every 1.33730109 seconds. She and her dissertation advisor, Antony Hewish, jokingly named the source Little Green Man, thinking of signs from an extraterrestrial civilization. This, at least, seemed to Hewish to be the most obvious explanation for the rapid succession of radio pulses from the constellation Vulpecula.

Soon, however, Hewish and Bell ruled out aliens as the cause. The researchers eventually discovered the real explanation: it is a compact object, a neutron star, that rotates extremely rapidly. It has a diameter of about 20 kilometers, but its mass is approximately that of our Sun. This makes neutron stars the densest of the celestial bodies: a bit of matter the size of a cube of sugar would weigh around a billion tons on Earth.

Moreover, a neutron star is surrounded by a strong magnetic field that, similar to the one on Earth, is substantially bipolar. Along the axis of the magnetic field, these bodies emit radiation within a narrow cone. When the rotation axis and magnetic field axis are tilted toward each other, the beam sweeps through space like the beam of a lighthouse. If it happens to strike the Earth, short pulses are registered whose frequency corresponds to the rotation frequency of the celestial body. Neutron stars that become noticeable in this way are called pulsars.

700 REVOLUTIONS PER SECOND

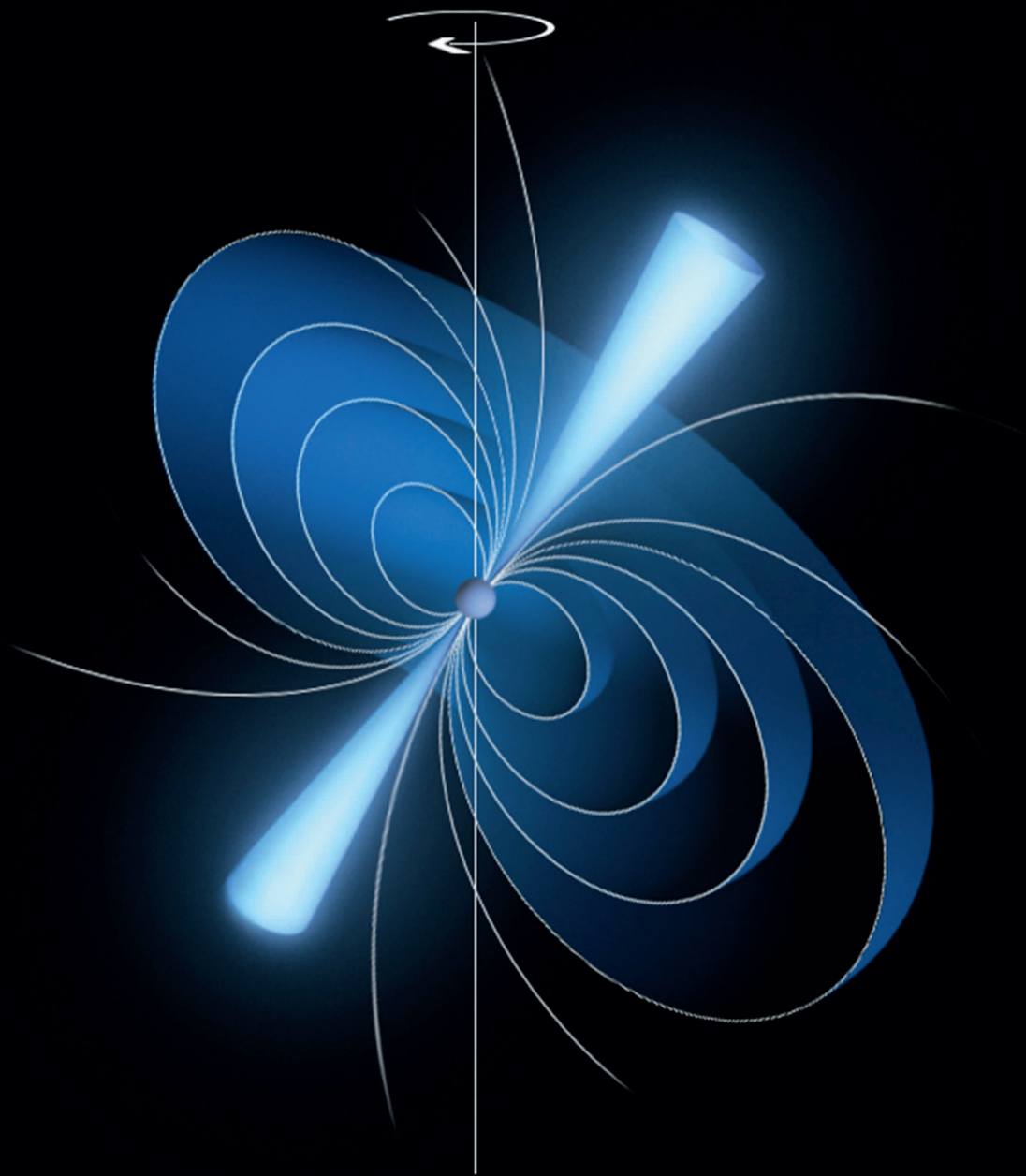
“Today, we know of around 2,200 pulsars with periods between 1.4 thousandths of a second and 8.5 seconds,” says Michael Kramer, who has been focusing on the physics of these cosmic lighthouses for two decades and is now a Director at the Max Planck Institute for Radio Astronomy in Bonn. So the fastest pulsar rotates about its own axis

more than 700 times per second. The theoretical maximum limit is around 2,000 revolutions per second; if it were any faster, centrifugal forces would tear it apart.

In the past decades, pulsars were detected in all regions of the electromagnetic spectrum – from the radio-wave to the gamma range. Still, it isn’t yet fully clear how the radiation is generated. Early this year, an international collaboration in which the Max Planck group in Bonn participated observed for the first time an unexpected correlation between radio and X-ray pulses: when the radio pulses are strong, the X-ray radiation is weak – and vice versa.

Surprisingly, this switch occurs within seconds. Thereafter, the whole thing remains stable in the new state for a few hours. The astronomers’ explanation for this variable behavior is that the two types of radiation are generated in different regions.

“On the surface of the pulsar, the electrical force induced by the magnet-



Spotlights in space: A neutron star rotates rapidly about its axis and, in the process, emits radiation that sweeps across space like the beam of a lighthouse. Astronomers currently know of about 2,200 such pulsars.



The inside of a giant dish: With a diameter of 100 meters, the radio telescope in Effelsberg is one of the largest facilities of its kind. Michael Kramer (left) and his colleague Norbert Wex use the instrument for their research.

ic field is several hundred billion times stronger than the gravitational force,” says Kramer. As a result, electrons are pulled out of the surface and captured by the magnetic field. The conditions are so extreme that positrons (antielectrons) are also formed, which have a positive charge. These race back to the surface and, upon impact, heat it up to millions of degrees. This results in the formation, at both magnetic poles, of a large hotspot that measures a few kilometers in size and emits X-ray radiation.

HELLISH SCENARIO WITH SWIRLING PLASMA

The electrons, on the other hand, remain trapped in the magnetic field and swirl around with the pulsar. The further away from the pulsar it is, the faster the plasma rotates. “At the distance at which it would nearly reach the speed of light, the magnetic field lines open into the expanse and the elec-

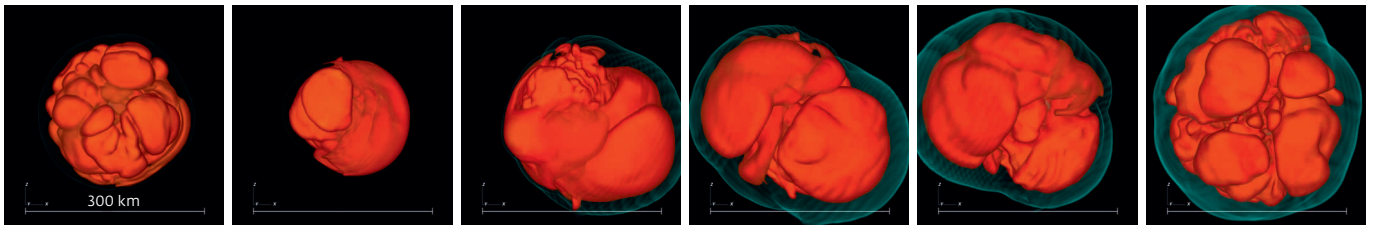
trons shoot into space in two cones, emitting radio radiation,” says Kramer, as he calmly sketches this hellish scenario on a piece of paper.

Researchers explain the latest observation of the switch between pulsed radio and X-ray radiation as being due to rearrangements of the approximately 100,000 kilometer magnetosphere within just a few seconds. Just exactly how this occurs and what triggers it isn’t completely clear. However, the fact that most pulsars tick extremely precisely despite such changes seems noteworthy. The regularity with which the pulses reach the Earth can definitely achieve the precision of atomic clocks.

This makes pulsars the best-suited celestial bodies for testing Einstein’s theory of general relativity. And this is precisely the task to which Michael Kramer’s Bonn-based Department of Fundamental Physics in Radio Astronomy is dedicated. Perhaps they will

even be the first to detect gravitational waves directly. But first things first. When Albert Einstein completed his theory of general relativity in 1915, the gravitational force – also referred to as gravitation – was no longer a force, but a geometric property of time and space. Celestial bodies curve the space around them, similar to how balls dent a stretched cloth. If another body enters such an area, it will deviate from a straight path and follow the curvature. The same applies to light. In addition, time near a star – that is, near a large curvature – passes more slowly than it does in open, flat space.

So far, Einstein’s theory has passed every test. Very precise tests are difficult, though, because the effects are relatively weak. The theory of general relativity has been tested in a variety of ways in our solar system, but particularly in regions of strong gravitation – that is, strong curvature – it has, to date, only rarely been put to the test.



Stellar turbulence: Researchers from the Max Planck Institute for Astrophysics use a three-dimensional computer simulation to illustrate the development of a neutron star at six points in time (0.154, 0.223, 0.240, 0.245, 0.249 and 0.278 seconds, from left). Characteristic, mushroom-like bubbles form in which neutrino-heated gas “cooks,” while the so-called accretion shock instability simultaneously causes wild pulsations and rotations of the entire heated matter layer (red) and the enveloping supernova shockwave (blue).

Pulsars, as the most compact celestial bodies known, offer unique opportunities. Only black holes could top them.

For such tests, the astronomers need pulsars in binary star systems. About one in every ten stars has a companion, but not all such systems are suitable. Most binary systems comprise a pulsar and a white dwarf, a burnt-out star that has shrunk to the size of the Earth. Since a white dwarf isn't nearly as compact as a neutron star, it also doesn't cause a very strong spatial curvature. Thus, systems comprising a pulsar and another neutron star are most suitable. The researchers know of about ten of these.

Astronomers discovered their absolute favorite one in 2003, using the Parkes radio telescope in Australia: the first and currently only system that consists of two pulsars. “It's really fortunate for us, because not only are the two pulsars like two extremely precise clocks, they also happen to have some particularly favorable characteristics,” says Kramer's colleague Norbert Wex, an expert on the relativity theory.

Both bodies have approximately the same weight and contain 1.3 solar masses. One of them takes 23 thousandths of a second to rotate once about its own axis, and the other 2.8 seconds. At a distance of 900,000 kilometers from one another, they are very close together – a good twice the distance between the moon and the Earth. But while the

moon requires 28 days to complete one orbit around the Earth, the two pulsars circle each other in less than two and a half hours – at a speed of around a million kilometers per hour.

LITMUS TEST FOR THE RELATIVITY THEORY

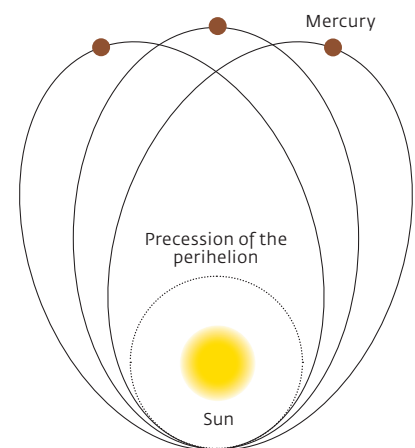
Michael Kramer and his colleagues belong to an international group of radio astronomers who regularly observe this double pulsar and use it to put Einstein's theory through its paces. For example, the orbit of the two pulsars rotates in space. This effect occurs in our solar system particularly strongly in the innermost planet Mercury.

The explanation of this so-called perihelion precession was the first triumph of Einstein's theory. But while it takes three million years for a complete period in the case of Mercury, it takes just 21 years for the double pulsar – a clear indication of how much stronger the effects of the relativity theory must be in this system.

Moreover, the astronomers are fortunate that they look almost directly at the edge of the orbit. This means that the two pulsars are nearly exactly one behind the other for every orbit. In this situation, the signal of the rear pulsar passes the one in front at a distance of just 20,000 kilometers. Since, in doing so, it has to pass through the spatial depression, its

path is extended – which is evidenced by a ten-thousandth of a second delay in the arrival time of the pulse. Thanks to the extreme synchronization of the two pulsar clocks, this effect can be precisely measured.

The researchers have since registered further phenomena predicted by the theory of general relativity. All of these findings confirm the theory to a precision of within a few per mil. Einstein's theory also postulates that two celestial bodies orbiting each other emit gravitational waves that propa-



In motion: The orbital point closest to the Sun (perihelion) of the planet Mercury isn't fixed in space, but rather migrates. Einstein predicted this perihelion precession precisely.



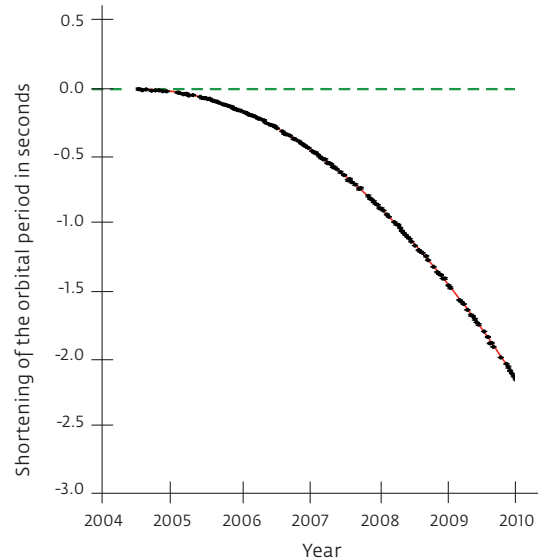
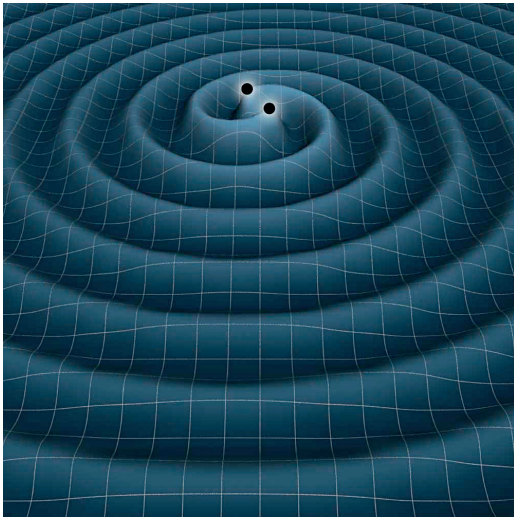
Situation briefing: In the control room of the Effelsberg radio telescope (in the background), Norbert Wex (left) and Michael Kramer discuss the results of their measurements.

gate at the speed of light. In the analogy with the dented cloth, they can be visualized as waves that go out from the double pulsar in, to put it in simplified terms, concentric waves – similar to the waves on the surface of a lake into which a stone has been thrown.

Due to the emission of gravitational waves, the two bodies lose a portion of their orbital energy. As a result, they slowly come closer together on a spiral-shaped path. “We discovered that this causes the orbit to shrink by 7.12 millimeters a year,” says Kramer, and adds with a grin: “with an uncertainty of nine-thousandths of a millimeter.” This incredible precision leads to the prediction that the two bodies will collide in 85 million years and merge together in a gigantic ball of fire.

More than 30 years ago already, American astronomers Russell Hulse and Joseph Taylor detected gravitational waves indirectly, in another binary star system with only one pulsar, based on the decrease in the orbiting time. They were awarded the Nobel Prize in Physics in 1993 for this achievement. The new measurement data from the double pulsars, however, is even more precise and is particularly well suited for testing alternative theories to Einstein’s crowning achievement.

The most well known example of one of these alternatives is likely the so-called MoND (modified Newtonian dynamics) theory of Israeli physicist Mordehai Milgrom. He had already modified the Newtonian law of gravity 30 years ago in such a way that it explains the rotation of spiral galaxies without the assumption of the hypothetical dark



Pas de deux in space: When two neutron stars dance about a common center of gravity, they emit gravitational waves (left). Because this causes both objects to continuously lose a portion of their orbital energy, they slowly approach each other on a spiral-shaped orbit, and their orbital periods grow shorter. The diagram at right shows these conditions for the double pulsar PSR J0737-3039.

matter. Then about ten years ago, theoretician Jacob Bekenstein gave Milgrom's theory a relativistic form by introducing, besides the curvature of space, two further auxiliary fields.

THE HUNT FOR GRAVITATIONAL WAVES

Bekenstein's alternative, called TeVeS, differs from Einstein's theory in the prediction of the emitted gravitational waves primarily in strong fields. That is why the double pulsar is uniquely suited for the acid test. The result is unambiguous: the measured values agree to within 0.05 percent with the prediction of the theory of general relativity. Bekenstein can explain this only if he assumes very specific, non-physical conditions. "In our view, this refutes TeVeS," says Norbert Wex, summarizing the results.

So once more, Einstein passed all tests with flying colors. But the Max Planck astronomers in Bonn have their sights set on another major goal – the direct detection of gravitational waves. And it goes like this: A gravitational wave compresses and stretches the space it crosses. In the process, the distances in this space are briefly shortened and

lengthened. Physicists have already been trying for some years now to measure such microdistortions using laser interferometers. GEO600, one of the instruments working in the international network, is located near Hanover and is operated by the Max Planck Institute for Gravitational Physics.

These instruments are designed for gravitational waves with frequencies between tens of hertz and a thousand hertz, corresponding to wavelengths between 100 and 10,000 kilometers. They should originate primarily from merging neutron stars and from black holes and exploding stars (supernovae). The radio astronomers in Bonn, in collaboration with colleagues from around the world working on the Pulsar Timing Array, want to expand this range on the order of nanohertz – that is, at wavelengths of tens of light-years.

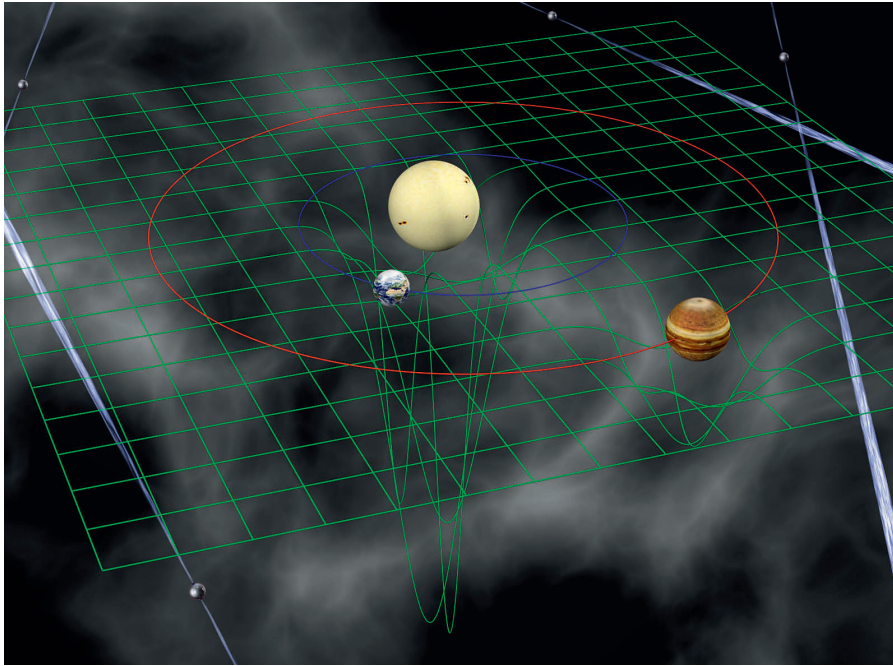
Here, the researchers are expecting signals from two merging, supermassive black holes, like those that exist in the centers of galaxies. "In the young universe, when the star systems were even closer together, there should have been more frequent collisions and mergers of black holes," says Michael Kramer. But how can this be determined with pulsars?

When a gravitational wave approaches Earth, it distorts the space in the vicinity of the solar system and changes the distances between the incoming pulsar signals. Due to a special quirk of these waves, the distance is diminished in one direction and increased in the perpendicular direction. This is expressed in a change in the arrival times of the pulsar signals that is correlated in the sky: while the signals from the one direction arrive earlier than normal, the signals that come from a region of the sky that is offset by 90 degrees arrive later.

COSMIC LIGHTHOUSES ILLUMINATE THE ASTRONOMERS

For their search for gravitational waves, the astronomers need around 40 pulsars with maximum precision throughout the sky. They are currently observing about 30 to determine their precision over the course of the experiment. To track down further cosmic lighthouses, the researchers in Bonn are collaborating intensively with their colleague Holger Pletsch at the Max Planck Institute for Gravitational Physics in Hanover.

Pletsch, who was recently awarded the Heinz Maier-Leibnitz Prize, developed a method for analyzing the enor-



Weighing the solar system: The masses of the Sun and planets curve space and thus influence the arrival time of pulsar signals on Earth. By correcting the time error of the pulsar signals, the masses of the planets can be estimated with great precision. The measurement method is complicated and is shown here merely as a schematic diagram.

time, to weigh planets in their entirety, including all moons and rings,” says Champion. And they did it with a precision that was previously possible only with space probes.

For the Pulsar Timing Array, the radio astronomers are currently using multiple antennas that are distributed throughout the world, including the 100-meter radio telescope in Effelsberg. Starting in the next decade, they will have access to the new Square Kilometre Array (SKA) being developed in South Africa and Australia. The final design will be a hundred times more sensitive than the “giant of Effelsberg.”

“If we don’t detect any gravitational waves with the SKA, then there’s something wrong,” says Michael Kramer. In that case, either the cosmologists’ models for the merging of black holes in the young universe would be incorrect, or Albert Einstein would have been wrong after all with his prediction of gravitational waves. But the radio astronomers in Bonn almost entirely rule out the second possibility. ◀

mous amounts of data from gravitational wave detectors like GEO600. But it can also be used to track down the beeps of the pulsars in the radio telescope data. “We’ve already found more than ten additional pulsars with this method,” says Kramer.

THE CURVATURE OF SPACE CAN’T BE NEGLECTED

However, only a few pulsars are suitable for this project, as the researchers have to record the pulses over a number of years with an accuracy of better than 100 nanoseconds. Moreover, they have to take into account the curvature of space caused by the bodies in our solar system, as it, too, delays the arrival time of the signals. If, for instance, the mass of Jupiter isn’t known precisely enough, then the solar system’s center of gravity isn’t known exactly either. As a result, the calculated arrival times fluctuate precisely with Jupiter’s orbital period.

For this reason, an international team headed by Kramer’s colleague David Champion undertook a precise measurement of the masses of the giant planets. “This allowed us, for the first

TO THE POINT

- Astronomers currently know of around 2,200 pulsars, or compact neutron stars.
- Due to their large gravitational force and their uniquely precise rotation, pulsars are suitable for all kinds of physics tests.
- Researchers check, for example, statements from the theory of general relativity, or test alternative models to Einstein’s ideas.
- Pulsars also serve in directly detecting gravitational waves, though none have been found yet.

GLOSSARY

Theory of general relativity (TGR): The theory presented by Albert Einstein (1879 to 1955) in 1915 describes the interaction of matter with space and time. A key player in the TGR is gravitation, which is considered to be a geometric property of curved, four-dimensional space-time.

GEO600: The installation in a field outside Ruthe, near Hanover, comprises two 600-meter-long trenches covered with corrugated sheet metal. Inside these run the beams of a laser; they are reflected at the ends of the tubes, converge again at the beam splitter, and strike a detector there. If gravitational waves pass through the installation, the space-time will be compressed, and the light will exhibit tiny but measurable run-time differences.

Neutron star: When a star has used up its fuel, energy production stops. The gas pressure disappears, and the gravitational force causes the interior of the star to collapse within fractions of a second. If the mass of this nucleus is between 1.4 and about 3 solar masses, a neutron star forms. Less massive stars end up as white dwarves, and heavier ones as black holes. The outer shell is blasted into space, lighting up as a supernova.

Square Kilometre Array (SKA): The Square Kilometre Array is a radio telescope with a total collection surface of around one square kilometer. Its sensitivity is expected to be many times that of conventional antennas. Furthermore, this facility will allow astronomers to scan the sky ten thousand times faster than before. The SKA is being built in South Africa and Australia and is expected to be fully completed in 2023.

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